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Self-aggregation of Deep Convection and its Implications for Climate

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Abstract *Purpose of Review* This paper reviews the self-aggregation of deep convection, its impact on the large-scale environment, its dependence on surface temperature, and its implications for climate.
Recent Findings Self-aggregation generates significant humidity variability, dries the mean state, reduces high cloud cover, and increases the ability of the atmosphere to cool to space. Some studies find that convection is more self-aggregated at warmer temperatures but other studies, or other ways of measuring the degree of self-aggregation, disagree. There is not a simple, monotonic relationship between self-aggregation and surface temperature.
Summary Self-aggregation, through its effect on the humidity distribution and radiative budget, can affect climate. However, there is uncertainty over how strong the modulation of climate by self-aggregation is, in part because of the ambiguity over its temperature dependence. There are some indications that self-aggregation may modestly reduce climate sensitivity even without a dramatic temperature dependence, but more research is needed to understand this behavior.

Keywords self-aggregation · Convective organization · Radiative-convective equilibrium · Climate sensitivity · Cloud feedback · Tropical convection

1 Introduction

Tropical convection organizes across a wide range of scales, driven by a variety of physical mechanisms. One type of organization that arises in idealized numerical simulations is *self-aggregation*, which is the spontaneous organization of convection into one or several long-lasting clusters surrounded by large areas of dry air that occurs despite spatially homogeneous boundary conditions and forcing. This phenomenon first emerged in simulations with two-dimensional cloud-resolving models configured in radiative-convective equilibrium (RCE), an idealization of the tropical atmosphere in which convection balances the radiative heat loss of the atmosphere [1]. It has subsequently been found to occur in RCE simulations with a wide variety of model types and configurations, from two- and three-dimensional limited area cloud-resolving models with domain lengths of O(10^2 – 10^4) km[2–22], regional and global models with parameterized clouds and convection [23–35], and global models with super-parameterized or explicit convection [36–38]. There are many processes capable of organizing convection, including external influences like wind shear and sea surface temperature (SST) gradients, but self-aggregation is distinct from these mechanisms of organization and instead represents a fundamental instability of the RCE state. It arises due to interactions between radiation, environmental moisture, surface enthalpy fluxes and the convection itself [11, 39]. A significant body of research in recent years has focused on elucidating the precise physical mechanisms leading to the self-aggregation of deep cumulus convection, which was thoroughly reviewed by Wing et al. [40]. One robust result is that feedbacks involving longwave radiation and water vapor and/or clouds are essential for triggering and maintaining self-aggregation [2, 6, 9, 11, 13–15, 21, 28, 35, 37, 39, 41, 42]. Uncertainties remain about the details of the physical mechanisms [40]; for example, several recent studies have emphasized the importance of boundary layer processes and shallow circu-

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lations [13,18,21,28,43] but the relative role of energy transport by shallow circulations compared to diabatic processes in the free troposphere is still debated [6, 11,14,15,28,35,37]. It is possible that different mechanisms drive self-aggregation in different parameter regimes. Shallow cumulus convection also has been found to self-aggregate in idealized large eddy simulations, but the driving mechanism is different than for deep convection [44], which is the focus of this paper.

It remains an open question as to exactly how self-aggregation is manifested in the real atmosphere, but a recent review by Holloway et al. [45] argued that the behavior of self-aggregation in models *is* relevant to real-world convection and climate. Holloway et al. [45] confronted the apparent contradictions between modeled self-aggregation and observed organized convection in terms of time scales, initial conditions, and mean state extremes, noting that the e-folding time of O(10) days for self-aggregation includes the spin-up of small-scale convective activity and would lead to larger scales in a given amount of time when starting from existing asymmetries, as is typically found in nature. Self-aggregation is therefore thought to be related to large-scale phenomena like the Madden-Julian Oscillation (MJO) [37,51, 52] and the formation of tropical cyclones [53,54]. Holloway et al. [45] also found that some simulations of self-aggregation have realistic representations of atmospheric humidity variability (though there is no guarantee that this is for the right reason). The study of self-aggregation in models has lead to new insights into processes that allow convection to interact with its environment, motivating new ideas about how organized convection interacts with climate [16,30,31,34,55–58]. The processes that drive self-aggregation in idealized model simulations have also begun to be investigated in simulations with realistic tropical variability [46,47] and in observations [48–50].

One feature that is clear across all studies of self-aggregation is that the transition to self-aggregated convection results in profound changes to the domain-mean environment [6,14]. This, combined with evidence that the existence or degree of self-aggregation may be temperature dependent [11,28,30,33,34,39,59], indicates that self-aggregation may be important for the properties of the climate system. This will be the focus of this paper. First, I review the impact of self-aggregation on the large-scale environment, including changes to the atmospheric energy budget, moisture distribution, and cloudiness (Section 2). Next, I discuss the challenges inherent in determining whether self-aggregation is temperature dependent and the evidence that suggests it is favored at warmer temperatures (Section 3). Finally, I synthesize what implications the impacts and temperature dependence of self-aggregation have for climate and describe whether it can and does modulate climate sensitivity (Section 4), before concluding with a summary and discussion of steps forward (Section 5).

2 Impact on Large-Scale Environment

2.1 Simulations

It has has long been known that organized convection in nature contributes a significant fraction of total tropical cloudiness and precipitation [60–63], modulates the diabatic heating of the atmosphere [64], and therefore influences the large-scale circulation, moisture distribution, and hydrological cycle [65,66]. It is therefore not surprising that the self-aggregation of deep convection found in numerical simulations is not just a spatial reorganization of convection, but instead has substantial impacts on the large-scale environment (which is the domain-mean of limited area simulations).

One of the most apparent and oft-cited identifying features of self-aggregation is the drying of the non-convective environment and increase in the spatial variability of moisture (the dry regions get drier, and the moist regions get moister). As convection self-aggregates, the area of dry, subsiding air expands to cover more than half the domain [28,30,33,34,57]. Since the domain mean is dominated by the dry areas, self-aggregation results in a dramatic drying of the mean state [6,14]. The decrease in free-tropospheric relative humidity occurs at nearly all heights, but peaks in the middle troposphere (Figure 1).

Various measures have been used to quantify the increase in the spread of the moisture distribution associated with self-aggregation, such as the interquartile range of precipitable water [6,9,15,16,37], the spatial variance of column-integrated moist static energy [11, 14], and the spatial variance of column relative humidity [14,67] (Figure 2). All increase as convection self-aggregates. The spread between moist and dry regions is not only seen in column-integrated quantities; profiles of water vapor mixing ratio and relative humidity indicate that the dry regions are drier throughout most of the depth of the troposphere [45].

By drying the mean state and enhancing the dryness of dry regions, self-aggregated convection makes the system more efficient at radiating heat, which has significant implications for the regulation of tropical energy balance and global climate [68]. For example, the domain mean outgoing longwave radiation increases by 10-30 Wm^{-2} when convection is self-aggregated [11,14]. self-aggregation is also associated with domain-mean warming of several degrees in the free troposphere [6,

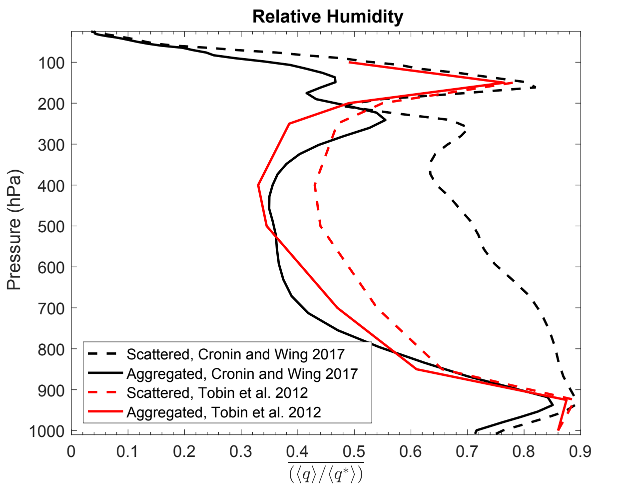

Fig. 1 Mean relative humidity profiles for scattered (dashed) and self-aggregated (solid) convection. The black lines show domain-mean profiles from the 300 K channel simulation from Cronin and Wing [57], where the dashed line is the initial sounding (an average of an unaggregated small-domain simulation) and the solid line is an average over the last 25 days of the self-aggregated channel simulation. The red lines show relative humidity profiles from satellite observations of scattered and self-aggregated convection, adapted from Tobin et al [70].

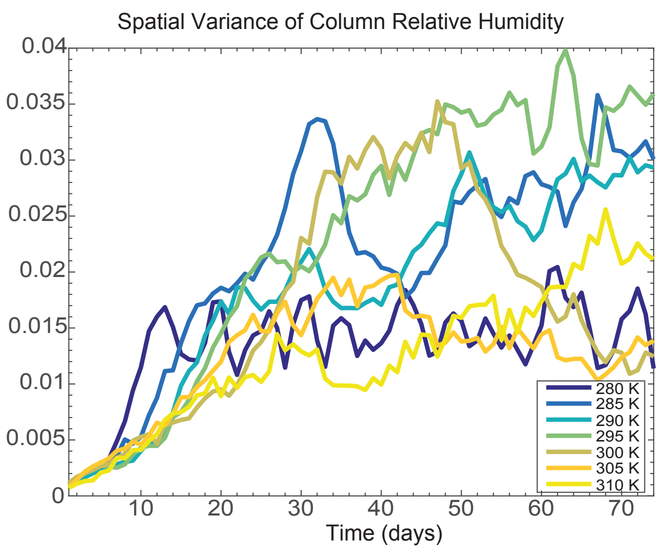

Fig. 2 Increase in the spatial variance of column relative humidity as the simulation progresses and convection becomes self-aggregated, in the channel simulations from Cronin and Wing [57].

14], because the local region in which convection occurs (which sets the domain-mean temperature), is moister when convection is self-aggregated. Parcels rising from a moister boundary layer follow a warmer moist adiabat, and a moister free troposphere in the vicinity of convection reduces the influence of entrainment and drives the troposphere closer to a moist adiabat - both act to warm the troposphere.

In concert with the development of large areas of dry, subsiding air, self-aggregation generates large-scale overturning circulations. In some simulations, these circulations bear a striking resemblance to the observed distribution of large-scale vertical velocity in the tropics [57].

Self-aggregation also leads to changes in the cloud distribution, most notably a reduced coverage of high clouds [14,57]. The reduction in high cloud fraction (and cloud water concentration) is found both as convection transitions to a self-aggregated state in an individual simulation [14] and when one compares pairs of unaggregated and self-aggregated simulations [57]. While self-aggregation reduces the absolute amount of high cloud cover, it does not significantly change the response of high clouds to warming (usually, though not always, found to be a decrease) [30,57]. Mid-level cloudiness is also found to be reduced by self-aggregation [57], but the change in low clouds is more uncertain. There is an increase in low cloud fraction and low-level cloud water with self-aggregation, [57] but at the resolutions typically used (~3 km), low clouds are not expected to be represented accurately. Further, RCE simulations lack realistic trade-cumulus and stratocumulus cloud regimes.

These cloud changes, combined with the changes to the humidity distribution, have consequences for the energy budget. As alluded to above, longwave emission to space is larger for self-aggregated states. However, due to the opposing responses of high and low level clouds to self-aggregation, the reflected shortwave radiation changes little and the net radiative flux into the top of the atmosphere is reduced [14,69]. Self-aggregation results in an increase in tropospheric radiative cooling and a decrease in energy gain by the surface [14]. Simulations at fixed sea surface temperature indicate that surface enthalpy fluxes are enhanced, because of stronger wind speeds in the convective region and larger air-sea enthalpy disequilibrium in the dry, non-convective area. However, the behavior of the surface energy budget with self-aggregation may be substantially different when surface temperature is allowed to evolve [16,34].

Finally, self-aggregation affects the hydrological cycle: mean precipitation is about 23% larger in simulations with self-aggregation compared to those without [57], consistent with both a higher precipitation efficiency and larger atmospheric radiative cooling and surface enthalpy fluxes in when convection is self-aggregated. Cronin and Wing [57] found that changes in both mean and extreme precipitation with warming are similar between unaggregated and self-aggregated cloud-resolving simulations, but Pendergrass et al. [31] found that the rate of increase in extreme precipitation with warming varied with the degree of self-aggregation in general circulation model (GCM) simulations. Self-aggregation therefore may modulate the hydrological cycle and its sensitivity to climate.

In summary, self-aggregation of convection generates significant humidity variability, dries the mean state, reduces high cloud cover, and increases the ability of the atmosphere to cool to space, all of which lead to the potential for it to impact climate.

2.2 Observations

Similar relationships are also found in observations of aggregated convection [70, 58, 72], which may be aggregated by any mechanism. While this is not evidence that self-aggregation is occurring in nature, it does indicate that the relationships between simulated self-aggregation and the simulated large-scale environment are plausible. Aggregated convection (without reference to the mechanism that caused it) is classified in observations by a clustering metric derived from geostationary satellite brightness temperatures [70, 58]. The environment of a limited area region with open boundaries can then be compared between aggregated and scattered states, controlling for differences in convective intensity, sea surface temperatures, and large-scale vertical velocity [70, 58].

These observational analyses have found that, similar to simulations of self-aggregation, more aggregated states have a drier free troposphere in the non-convective environment and domain as a whole [58, 70] (Figure 1), large outgoing longwave radiation [48, 58, 70], reduced coverage of high clouds [48, 58, 70, 72], and larger tropospheric radiative cooling [58]. Note that while the relative humidity profile for the scattered observed convection (dashed red line in Figure 1) is moister than the analogous profile for scattered simulated convection (dashed black line in Figure 1), the "scattered" observed convection [70] is not necessarily completely unaggregated, it is just less aggregated than its "aggregated" counterpart. On the other hand, the "scattered" simulated convection [57] is nearly randomly distributed. The conclusion is robust to these discrepancies: in both observations and simulations, the more aggregated conditions, whatever their cause, are drier.

Observational analyses find mixed results with respect to low cloud fraction, in part because estimating low level cloud cover from satellite data is not straightforward due to cloud overlap and detection issues. On synoptic scales, using coarse-resolution brightness temperature data, Tobin et al. [70] found a decrease in total cloud fraction (including a decrease in low cloud fraction) in more aggregated states. Higher resolution brightness temperature data, CloudSat/CALISPO data, and MODIS data, on the other hand, indicate an increase in low cloud coverage in more aggregated states, similar to model simulations of self-aggregation.[48, 58, 72]. In contrast to simulations of self-aggregation, observational analyses of aggregated convection find an increase in the energy gain by the surface [58], little change in surface enthalpy fluxes [58, 70], and little change in the top-of-atmosphere radiation budget (an increase in longwave emission to space in more aggregated states is compensated by a reduction in reflected shortwave radiation, due to a decrease in cloud cover [48, 58, 70]).

With regards to the hydrological cycle, there is observational evidence that most of the regional increases in tropical precipitation over the last 30 years are associated with an increase in the frequency of organized convection [66, 73], though again the mechanism of organization is not specified. Observations from a tropical observing site indicate that the large-scale structure of the atmosphere in "moisture space", including a shallow overturning circulation between moist and dry columns, is similar to that identified in simulations of self-aggregation [50]. This suggests that the mechanisms of self-aggregation in idealized simulations may also be relevant to explaining large-scale features of the tropics [71].

3 Temperature Dependence

The idea that the self-aggregation of convection might be temperature dependent arose early on in the study of the phenomenon. Based on two-dimensional cloud-resolving simulations with fixed sea surface temperature (SST) and no mean wind, Held et al. [1] found that the spontaneous localization of convection took place more slowly at cooler SSTs. This indication of temperature dependence was investigated more systematically by Khairoutdinov and Emanuel [59], who found that in a three-dimensional cloud resolving model, self-aggregation only occurred above a threshold temperature. Later work supported the idea that self-aggregation was favored by warm SSTs [11], and a simple two-layer model based on a longwave radiation - water vapor feedback was proposed to explain this temperature dependence [39]. In the Emanuel et al. [39] two-layer model, when the lower troposphere longwave opacity is high, the net longwave cooling of the atmosphere decreases with increasing water vapor; a positive feedback that amplifies humidity perturbations. The condition of high lower tropospheric opacity is satisfied at high temperatures, where water vapor content is sufficiently large.

Subsequent studies have supported the idea that self-aggregation does depend on temperature in some manner, but the nature of that dependence seems to be more nuanced than originally thought - it is unlikely that the self-aggregation process turns on or off at a specific temperature threshold [14, 15, 28, 30, 34, 57].

One of the challenges in assessing the temperature dependence of self-aggregation is that in studies that perform three-dimensional cloud-resolving simulations over limited area, doubly periodic square domains, self-aggregation tends to be a discrete transition; with a few exceptions, it generates a single convective cluster and it either happens or it doesn't. Whether or not self-aggregation occurs is sensitive to many details of the simulation (for example, the domain size and horizontal resolution [9] and the choice of sub-grid scale scheme [17]), though this sensitivity could be a result of being near a critical threshold for transition to self-aggregated convection. The supposed temperature threshold for self-aggregation ($\sim$ 300 K) [11, 39] was called into question when other studies found self-aggregation to be insensitive to SST. Self-aggregation was found to occur at SSTs of 295 and 290 K in other square cloud-resolving simulations [15], at all SSTs between 280 and 310 K in 3D elongated channel cloud-resolving simulations [14], and at all SSTs between 290 and 325 K in 2D cloud-resolving simulations [21]. In addition, in uniform-SST (though not quite RCE) aquaplanet simulations with a super-parameterized GCM, a MJO-like signal (possibly arising due to self-aggregation mechanisms) was found at temperatures as cold as 274 K [74]. Self-aggregation has even been found to occur at temperatures near 240 K [12] - clearly, its existence is not restricted to "warm" SSTs.

While a radiative-convective instability driven by a longwave radiative feedback can manifest as self-aggregation and is temperature dependent [39], clouds and the vertical structure of the humidity perturbations can strongly modulate this instability [41]. Further, the longwave-water vapor feedback is not the only process occurring. There are other physical mechanisms (such as surface flux - wind speed feedbacks, and cloud-radiative feedbacks) that may act across all temperatures or may even be stronger at colder temperatures. While self-aggregation may occur at both cold and warm temperatures, the physical mechanisms that instigate it may be different, and clouds seem to be of primary importance [14, 28]. For example, Coppin and Bony [28] found in a GCM that at low SSTs, strong cooling from low clouds in the subsidence region lead to the formation of radiatively-driven cold pools and a low-level overturning circulation that drove self-aggregation, but at high SSTs, interactions between surface enthalpy fluxes and surface winds were responsible for the initiation of self-aggregation. In that particular model, though, the low-cloud, radiation and circulation coupling is weaker at higher SST because the low-cloud amount itself decreases strongly with increasing SST. This may not be generalizable to other models; indeed, Becker et al [33] found the opposite in a different GCM, with the surface flux-wind feedback being most important for self-aggregation at low SSTs and the moisture-convection feedback and a low-level overturning circulation contributing at high SSTs.

It remains possible that the degree, rather than the existence, of self-aggregation depends on temperature. This can only be reliably assessed in simulations that generate more than one convective region. Objectively measuring the strength of self-aggregation, however, is challenging. There is no single agreed upon metric; rather, there are at least three general classes of indices, each of which reflect a different component of self-aggregation. Humidity-related indices, such as the spatial variance of column relative humidity (Figure 2), reflect the clear signature of self-aggregation in broadening the moisture distribution [14]. The subsidence fraction (Figure 3), the fractional area of the domain covered by large-scale subsidence, is related to the transition of the vertical velocity distribution to small areas of strong ascent surrounded by large areas of weak subsidence [28, 30, 33, 57]. Moist convection, of course, always has a skewed vertical velocity distribution, but this only emerges in spatiotemporal averages of vertical velocity when the updrafts are strongly organized in space and time, as they are when convection is self-aggregated. A third type of index is the "organization index", which measures the degree of clustering of convection compared to a random distribution. This index has the advantage of having a theoretical null to compare against, and thus quantitative meaning, but captures multiple scales of organization - both the large-scale moist and dry patches *and* the smaller-scale clustering within them [17, 57].

These different metrics measure different things and sometimes give opposite results; for example, in a set of elongated channel cloud-resolving simulations, the organization index indicated a tendency for convection to be more self-aggregated at higher SSTs, while the subsidence fraction was non-monotonic with temperature but suggested a tendency towards *less* self-aggregation at higher SSTs [57], and the variance of column relative humidity suggested no obvious temperature dependence [14]. It is not obvious which of the above metrics for the degree of self-aggregation is most appropriate, so, at minimum, studies should employ several metrics that capture different aspects of self-aggregation and compare the results. If only a single metric is used, care must be taken if trying to make clear inference about variability in the degree of self-aggregation. More thoughts on ways to improve metrics of self-aggregation are presented in Section 5.

GCM studies generally have shown simulations at the highest temperatures to be most strongly self-aggregated [28,30,31,34], though this is sensitive to the details of the convective parameterization [33]. Figure 3 summarizes results from six different sets of simulations in three different studies that all used subsidence fraction to measure the degree of self-aggregation. There is a wide range of values of subsidence fraction across the different sets of simulations (higher values above 0.5 indicate more strongly self-aggregated convection). The Cronin and Wing [57] cloud-resolving simulations indicate a decrease in self-aggregation with SST, while two of the Becker et al. [33] sets of GCM simulations (with either no convective parameterization or no entrainment) indicate no dependence on SST. On the other hand, the other two Becker et al. [33] sets of GCM simulations (with reasonable values of entrainment) suggest that self-aggregation increases towards the coldest and warmest SSTs, which is similar to, but less extreme than the variability across SST found in the Coppin and Bony [34] GCM simulations. Given these disagreements, and the fact that each indicate that over some large range in SST, the degree of self-aggregation does not vary much at all, the null hypothesis that the degree of self-aggregation does not depend systematically on SST seems as easily justified as any other option.

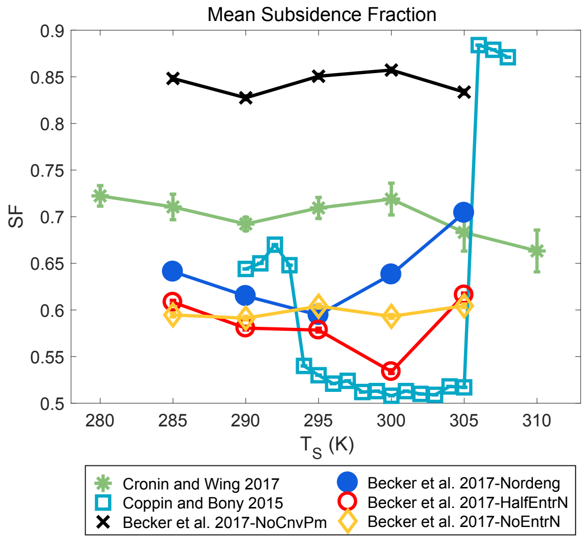

Fig. 3 A metric for the degree of self-aggregation, subsidence fraction, for simulations at different sea surface temperatures. The green asterisks indicate cloud-resolving simulations from Cronin and Wing [57], where subsidence fraction is defined based on the vertical velocity at 500 hPa averaged over 96 x 96 km^2 blocks and 1 day. The average over the last 25 days of each simulation is shown. The cyan squares indicate GCM simulations from Coppin and Bony [28], where subsidence fraction is defined based on large-scale vertical velocity at 500 hPa, and is averaged over the last 6 months of each simulation. The remaining symbols/lines indicate GCM simulations from Becker et al. [33], with four different convective parameterizations: no convective parameterization (black crosses), Nordeng scheme (blue filled circles), Nordeng scheme with halved entrainment rate (red open circles), and Nordeng scheme with no entrainment (yellow diamonds). In the Becker et al. [33] simulations, subsidence fraction is defined based on the mass-weighted vertically integrated (1000 - 200 hPa) and daily averaged vertical velocity.

The degree of self-aggregation is not the only aspect of self-aggregation that may be temperature dependent: several studies have found a clear tendency in the scale of self-aggregation with SST. In 3D elongated channel simulations, the scale of self-aggregation (of $O(10^3$ km)) decreases with warming between 280 and 310K [14]. Similar results were found in 2D simulations, though in those simulations, the scale of self-aggregation increased significantly with SST above 310K [21], so the scale dependence may not be monotonic across all temperatures. There is currently no accepted theory for what sets the scale of self-aggregation, though several relating to boundary layer processes have been proposed [14,20,21,35] and a budget for the size of self-aggregation was recently developed [75].

A limitation is that most of the work performed on the temperature dependence of self-aggregation has used fixed SSTs. Several studies suggest a link between ocean coupling and the sensitivity of self-aggregation to SST. Generally, ocean coupling has been found to delay or prevent self-aggregation [6,16], although Reed et al. [27] found that GCM simulations with a slab ocean and cool SSTs resulted in *more* self-aggregation than simulations with similar but fixed SSTs and Hohenegger and Stevens [18] found that self-aggregation can be non-monotonic with surface heat capacity. Coppin and Bony [34] found that significant internal variability results from interactions between mean SST, SST gradients, and self-aggregation, suggesting that coupling between self-aggregation of convection and SSTs could contribute to interannual variability in the tropical atmosphere. In that study, the degree of self-aggregation was found to increase with climate warming on multi-decadal time scales, but was out of phase with SST on interannual time scales. Coppin and Bony [76] found that self-aggregation was *more* sensitive to SST in simulations with an interactive surface.

In summary, it is clear that various aspects of self-aggregation (its strength, its scale, its physical mechanisms) can and do depend on temperature, but the precise nature of this temperature dependence is *not* clear. The evidence to date suggests that there is not likely a simple, monotonic relationship between self-aggregation and temperature, so it is premature to say whether convection becomes more strongly self-aggregated with warming.

4 Implications for Climate Sensitivity

The significant impact that self-aggregation has on the humidity distribution and energy budget of the large-scale environment and the possibility that the tendency to self-aggregate is temperature dependent each have implications for climate sensitivity. Since self-aggregation enhances the ability of the atmosphere to cool to space, it is thought to stabilize climate, and was first proposed to act as a tropical thermostat by Khairoutdinov and Emanuel [59]. They proposed that a strong, nonlinear dependence of self-aggregation on SST would lead to tropical convection being in a state of self-organized criticality. They hypothesized that as convection self-aggregates, the atmosphere dries and cools more to space, which would decrease the SST. In turn, this could *disaggregate* convection. As convection disaggregates, the atmosphere would re-moisten, reducing cooling, and warming the system. The tropics would be attracted to the critical transition between self-aggregated and unaggregated states, regulating the tropical climate.

For self-aggregation to regulate tropical climate in this way, a series of behaviors and responses must occur. As described in Section 2, self-aggregation dries the atmosphere, and the drier dry regions efficiently radiatively cool to space (analogous to Pierrehumbert's [68] radiator fins). If the surface temperature is allowed to vary, this decreases the SST [6, 16, 59]. However, self-aggregation has been found to exhibit hysteresis, remaining aggregated when starting from an aggregated state even in an environment that may not support self-aggregation from homogenous initial conditions [9, 13, 28, 59]. Further, the sensitivity of self-aggregation to SST remains uncertain, as discussed in Section 3.

If convection does respond to climate warming by becoming more self-aggregated, the radiative impact of the drying and reduction in high clouds associated with self-aggregation could act as a negative feedback, reducing climate sensitivity. Specifically, an increase in the degree of self-aggregation combined with a large difference in top-of-atmosphere radiative flux between self-aggregated and unaggregated states could give rise to a strong negative climate feedback. Modeling studies indicate that the difference in net top-of-atmosphere radiative flux between aggregated and unaggregated states is large and negative [14], but this is not necessarily seen in observations [58, 70], due to compensation between longwave and shortwave fluxes (as discussed in Section 2).

Nevertheless, this idea was tested by Mauritsen and Stevens [55], who prescribed a *hypothetical* self-aggregation-related iris effect in GCM simulations and found that it modestly reduced climate sensitivity. This study did not provide evidence that self-aggregation increases with warming and increases cooling to space, but rather parameterized this effect by forcing the precipitation efficiency to increase with surface temperature, and showed that this leads to a modest negative climate feedback. Other studies have also made a connection between self-aggregation and reduced climate sensitivity. Becker et al. [33] found that GCM simulations with strong self-aggregation tended to have smaller climate sensitivities. In their simulations, different degrees of self-aggregation emerged from the use of different ways of parameterizing convection (specifically, the amount of entrainment). Hohenegger and Stevens [16], using coupled simulations with a cloud-resolving model, found that the emergence of self-aggregation prevented a runaway greenhouse effect and stabilized climate. Cronin and Wing [57] took a different approach and compared two sets of cloud-resolving simulations over a wide range of fixed SSTs: one set that exhibited self-aggregation across all SSTs, and one set that was unaggregated (due to its small domain size). They found that the net climate feedback parameter was more negative in simulations with self-aggregation than without, suggesting that self-aggregation reduces climate sensitivity (Figure 4).

However, the simulations examined by Cronin and Wing [57] did not exhibit a clear tendency to be more self-aggregated at higher SSTs. The reduction in climate sensitivity compared with unaggregated simulations may therefore be a result of the mere existence of self-aggregation, rather than changes in it with warming. This is a much subtler way for self-aggregation to influence climate sensitivity: by acting across all surface temperatures to dry the atmosphere, enhance the dryness of dry regions, and reduce high clouds. Cronin and Wing [57] proposed that the top of atmosphere radiation R could be considered as the sum of the net flux in the unaggregated state, $N(T)$, and the product of the degree of self-aggregation, $A(T)$ with the difference in top of atmosphere flux between self-aggregated and unaggregated states, $B(T)$. The total climate feedback is then given by

$$\lambda = \frac{dR}{dT} = \frac{dN}{dT} + A\frac{dB}{dT} + B\frac{dA}{dT} \quad (1)$$

where dN/dT is the climate feedback of the unaggregated state. Even if the degree of self-aggregation A

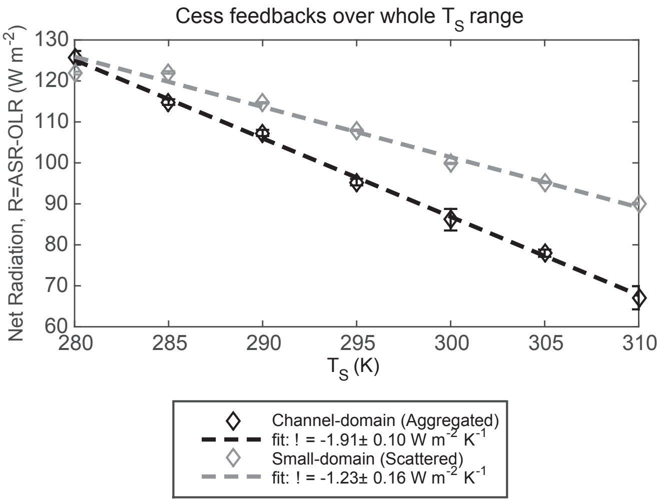

Fig. 4 Top-of-atmosphere net radiation against sea surface temperature for simulations with (black diamonds) and without (gray diamonds) self-aggregation, from Cronin and Wing [57] (their Figure 11a). The dashed lines indicate linear regressions to each, an estimate of the net climate (Cess-type) feedback.

does not change with warming, self-aggregation could still act as a negative climate feedback through the AdB/dT term. Physically, a moist adiabatic atmosphere with fixed, vertically uniform relative humidity has a stronger negative clear-sky longwave climate feedback when relative humidity is lower, (as it is when convection is self-aggregated [57]). Because the difference in clear-sky outgoing longwave radiation between moist and dry regions increases with warming, the drier dry regions in an self-aggregated basic state can yield a negative climate feedback compared to an unaggregated mean state (that is, B, which is negative because of self-aggregation [14, 69], becomes more negative with warming).

While this way that self-aggregation could modulate climate sensitivity may already be occurring in the present climate, the ability of climate models to represent self-aggregation and the response of the humidity distribution, which is sensitive to inherently uncertain parameterizations of convection, is questionable. Therefore, regardless of whether self-aggregation affects climate by affecting the mean state or by increasing in strength with warming, this response may not be adequately represented in current climate models. An additional uncertainty is that the impact of self-aggregation on climate sensitivity may be different when interactive surface temperatures are allowed [76].

In summary, self-aggregation certainly has the ability to affect climate, even without a dramatic temperature dependence, but the field is still at the early stages of determining how significant the effect of self-aggregation is and how much of it is already captured in climate model simulations, in part because the real and comprehensively-modeled tropics is far from homogeneously forced.

5 Conclusions

The role of convective self-aggregation in climate was identified by the World Climate Research Programme (WCRP) Grand Challenge on Clouds, Circulation, and Climate Sensitivity as one of the biggest unanswered questions in climate science [56]. The prospect that understanding self-aggregation may lead to an improved understanding of climate, in terms of modulation of climate sensitivity and the hydrological cycle and the narrowing of tropical rain belts, is intriguing. The physical mechanisms underlying self-aggregation - interaction between radiation, surface fluxes, clouds, and water vapor - may also be essential for understanding the Madden-Julian Oscillation [37, 51, 52, 77–82] and tropical cyclone formation [53, 54], two longstanding problems in tropical meteorology.

Substantial progress has been made towards mechanistic understanding of self-aggregation [40], but concerns remain over whether it has been robustly characterized and simulated, with known sensitivities to many aspects of the model set-up, including resolution and sub-grid parameterizations [9, 17, 33]. There is also a lack of understanding of what sets the spatial scale of self-aggregation, although there has been some recent progress in quantifying the scale and establishing theoretical frameworks for it [14, 15, 20, 21, 35, 75]. Of particular relevance to the impact of self-aggregation on climate, substantial uncertainties remain about how self-aggregation depends on temperature, with conflicting results in the literature. While there has been some recent progress on characterizing the behavior of self-aggregation with an interactive surface [16, 18, 34], the effects of an interactive surface are not yet completely understood. This may be especially important for elucidating a two-way interaction between self-aggregation and climate.

There are two key behaviors underlying the potential of self-aggregation to modulate climate:

1. The impact of self-aggregation on the large-scale environment, and
2. The temperature dependence of self-aggregation.

As reviewed in Section 2, self-aggregation reduces high cloud cover, dries the mean state, enhances the dryness of dry regions, and increases the ability of the atmosphere to cool to space. These results are robust across a wide variety of modeling and observational studies.

Our understanding of the temperature dependence of self-aggregation, as reviewed in Section 3, is much less certain. It is clear that self-aggregation can occur across a wide range of temperatures, but its strength, scale, and mechanisms may vary. There are disagreements between studies, and even between different metrics in the same study, as to whether the degree of self-aggregation increases or decreases with warming (or does not change).

The significant impact of self-aggregation on the humidity distribution and radiative budget has implications for climate sensitivity, but the lack of consensus on whether convection becomes more self-aggregated in a warmer climate prevents a robust conclusion on the climate impact of self-aggregation. However, even without a large change in the degree of self-aggregation with warming, it is still possible for it to modulate climate sensitivity through its effect on the mean state. The available evidence suggests that self-aggregation reduces climate sensitivity, but there are large uncertainties over how significant this effect is, how much of it is already captured in climate model simulations, and how it may be different with an interactive surface. Therefore, I conclude that self-aggregation may play a role in climate but more research, such as that outlined below, is needed to say what or how strong that role is.

One avenue of research that will help determine the role of self-aggregation in climate is the on-going Radiative-Convective Equilibrium Model Intercomparison Project (RCEMIP) [83]. RCEMIP includes an unprecedented collection of both convection-permitting models and those that parameterize convection, all configured in a consistent manner to simulate RCE. It will enable a much better understanding of the robustness of self-aggregation and whether the results discussed above generalize across a much wider range of models than have previously been used to study self-aggregation. RCEMIP will also better characterize the temperature dependence of self-aggregation across the spectrum of models, and, by comparing simulations with and without self-aggregation and applying new methodologies such as approximate radiative kernels for RCE [57], diagnose the impact of self-aggregation on climate sensitivity.

There have been relatively few studies of self-aggregation in a coupled framework because of the increased computational expense, but recent results indicate that an interactive surface, by allowing for additional modes of interaction between convection and its environment, may fundamentally change how self-aggregation depends on surface temperature and its implications for climate [34, 76]. This, combined with an interest in understanding the potential for self-aggregation over land surfaces and shallow mixed layer ocean areas, strongly argues for an increased emphasis on simulations with interactive surface temperatures.

The temperature dependence of self-aggregation would be easier to clarify if common and better metrics for defining the degree of self-aggregation were agreed upon and used. Of the three classes of metrics discussed here, humidity-related indices and subsidence fraction (due to the connection between large-scale subsidence and clear, dry areas that are efficient at radiatively cooling) seem most closely linked to the potential impact of self-aggregation on climate, and are simple to compute, but their quantitative values lack physical meaning. For example, the value of subsidence fraction is strongly sensitive to the spatiotemporal scales over which vertical velocity is averaged [57]. The organization index [17], which is more strongly grounded in theory, is a step in the right direction, but it captures multiple scales of organization so can be difficult to interpret (and is complicated to calculate). An additional limitation of all of these metrics is that none of them take into account the coherence of convecting regions in time, which is essential for establishing the large spatial variability of humidity associated with self-aggregation. If meaningful progress is to be made regarding the implications of self-aggregation for climate, a new, better metric for the degree of self-aggregation (as is relevant to climate) should be developed. This new metric should reflect the impact of self-aggregation on the humidity distribution, assess the temporal coherence of convection, be transparent about the scales being measured, and be applicable to both cloud-resolving models with limited area domains and global models with parameterized convection. The RCEMIP ensemble presents an opportunity to test a new metric across a wide range of models, domain geometries, and representations of self-aggregation.

These steps - a comprehensive intercomparison under RCEMIP, an improved metric for the degree of self-aggregation, more simulations with interactive surface temperatures - coupled with renewed interest in using RCE as an idealized framework for addressing fundamental questions about convection and climate [83] will position researchers well to leverage recent advances in understanding of self-aggregation of convection and determine its implications for climate.

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•• Wing and Cronin [14] examine the time scale, length scale, and physical mechanisms of self-aggregation in 3D cloud-resolving RCE channel simulations over a range of SSTs, as well as the impact of self-aggregation in the domain-mean.

•• Wing et al. [40] provide a comprehensive review of self-aggregation in numerical simulations, including its characteristics, driving physical mechanisms, and impacts.

•• Holloway et al. [45] provide a review of observational studies of processes related to self-aggregation, arguing that modeled self-aggregation is relevant to real-world convection and climate, as well as propose possible future directions for observational work related to self-aggregation.

•• Cronin and Wing [57] investigate the sensitivity of the degree of self-aggregation, clouds, and circulation strength to SST in 3D cloud-resolving RCE channel simulations, as well as estimate the climate sensitivity (and its modulation by self-aggregation) across those simulations.

• Honegger and Stevens [16] examine the behavior of self-aggregation in coupled RCE simulations with explicit and parameterized convection and show that self-aggregation stabilizes tropical climate.

• Coppin and Bony [28] discuss the different physical mechanisms that drive self-aggregation at different SSTs, in RCE simulations with a GCM, as well as introduce the subsidence fraction metric for self-aggregation.

• Becker et al. [33] investigate the sensitivity of self-aggregation to convective parameterization and SST in RCE simulations with a GCM, and diagnose the net climate feedback in simulations with strong or weak self-aggregation.

• Coppin and Bony [34] describe internal variability in RCE simulations with a coupled GCM that is driven by interactions between mean SST, SST gradients, and self-aggregation, finding that self-aggregation is out of phase with SST on interannual time scales.

• Stein et al [72] examine relationships between cloud cover and convective aggregation in satellite observations, providing observational evidence for relationships found in numerical simulations.